

## Structure and Dynamics of Coronal Plasmas

Grant NAGW-4081

## Progress Report

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## Progress Report

### I. Work Completed During the Past Year:

During the past year this grant has funded research by Drs. Golub and DeLuca, graduate student A. Daw and undergraduates Ms. Wills and Mr. Hartl. The following is a brief summary of the published papers, abstracts and talks which have been supported by Grant NAGW-4081 within the present grant performance period.

1. The paper "Observations and Modeling of the Solar Chromosphere Seen in Soft X-Ray Absorption by NIXT", by Daw, DeLuca and Golub, has been completed and has been accepted for publication in the Astrophysical Journal.

The Normal Incidence X-ray Telescope obtained a unique set of high resolution full disk solar images which were exposed simultaneously by X-rays in a passband at  $63.5 \text{ \AA}$  and by visible light. The perfect alignment of a photospheric visible light image with a coronal X-ray image enables us to present observations of X-ray intensity vs an accurately determined height above the visible limb. The height at which the observed X-ray intensity peaks varies from 4000 km in active regions to 9000 km in quiet regions of the sun. The interpretation of the observations stems from the previously established fact that, for the coronal loops, emission in the NIXT bandpass peaks sharply just above the footpoints. Because there is not a sharp peak in the observed X-ray intensity vs off limb height, we conclude that the loop footpoints, when viewed at the limb, are obscured by absorption in chromospheric material along the line of sight. We calculate the X-ray intensity vs height predicted by a number of different idealizations of the solar atmosphere, and we compare these calculations with the observed X-ray intensity vs height. The calculations use existing coronal and chromospheric models.

In order for the calculations to reproduce the observed off limb X-ray intensities, we are forced to assume an atmosphere in which the footpoints of coronal loops are interspersed along the line of sight with cooler chromospheric material extending to heights well above the loop footpoints. This means that coronal loop structures may be interpreted as isolated mini-atmospheres, with individual transition regions occurring at different heights, depending upon the coronal temperature and density values. We argue that the absorption coefficient for NIXT

X-rays by chromospheric material is roughly proportional to the neutral hydrogen density, and we estimate an average neutral hydrogen density and scale height implied by the data.

2. The paper "Soft X-Ray Absorption and Emission Associated with a Well-Resolved Quiescent Prominence Straddling the Solar Limb", by Gaizauskas, DeLuca, Golub, Jones and November, was presented at IAU Coll. No. 153 in Tokyo.

In this project, we have compared digitized images in chromospheric (ORSO,  $H\alpha$ ), transition region (NSO/KPNO HeI 10830), and coronal wavelengths (NIXT, 63.5 Å; CFHT optical continuum in the red) with photospheric magnetograms (NSO/KPNO) at the location of a filament on the SW limb at the time of the 11 July 1991 total eclipse. We find that a system of large-scale loops, visible in X-rays and Optical continuum over lies the filament and is rooted in patches of network near the high latitude limit of the southern belt of activity.

We report strong absorption of soft X-rays along the portion of the filament on the disk and in a small arch coincident with the portion of the filament that is projected against the sky over the limb. We see soft X-ray emission underneath the absorbing arch which we attribute to a source beyond the limb.

From the change in X-ray emissivity across the filament we estimate a minimum column density of  $6 \times 10^{19}$  neutral hydrogen atoms in the line-of-sight through the strongest absorbing features. The geometrical properties of the filament, derived from its projected height and width during its disk passage and at both limb transits, lead to an estimated volume density of  $3 \times 10^{10}$ . The visibility of the X-ray absorption feature implies X-ray emission beneath the filament. We conjecture that the faint emission is due to small-scale events involving magnetic reconnection along the polarity inversion line beneath the filament.

3. The paper "NIXT X-ray Bright Point Survey: Building a Better Bright Point", by Wills, Hartl, DeLuca and Golub, was presented at the Solar Physics Division meeting in Memphis in June 1995.

In this project, we have completed a survey of X-ray bright points in 63.5 Å coronal images from the 12 April 1993 NIXT rocket flight. We have identified 172 compact, isolated X-ray emitting regions as XBPs, a far larger number than were seen in earlier flights. We use contemporaneous BBSO magnetograms to determine the magnetic structure underlying the XBPs. Of our 172 points, 80 did not have an underlying bipolar feature. However, since most



of these points are within 0.2 solar radii of the limb, the lack of an underlying features maybe due to line-of-sight effects in the VMG. Of the 84 XBP's in the central region, we find that 83 show an underlying bipolar structure. With this statistically significant number of bright points, we can define the distribution in size, emitted x-ray flux, and solar latitude. We can also characterize the coronal and photospheric structure of the XBP's. Simple XBP's have only a single bipole underneath them, while complex XBP's show greater variation and structure in the bipolar region. The complex XBP's are about 10 of the total.

We have begun an examination of the dynamics of the magnetic flux associated with the XBP's by looking at sequences of BBSO images. Both converging and diverging magnetic elements are seen, but the converging elements are more common.

## II. Plans for the Current Year:

Our plans for continuation of this work during the current year include i) projects which are under development and which are expected to lead to presentations, either in oral or written form, within the year, and ii) completion of the projects described above by submission of papers to refereed journals.

Among the projects which are under development at the present time, we mention the following:

1. "A Converging Flux Model for Point-Like Brightenings Around Sunspots". In collaboration with E. Priest and C. Parnell, we are analyzing coronal, chromospheric and photospheric data of intense x-ray brightenings in Moving Magnetic Features around sunspots. The work includes development of an MHD model for energy release by reconnection, consistent with the observed evolution of the photospheric field, and with the observed coronal energy release parameters.

2. "High-Resolution Magnetic Field Extrapolations and Comparison with the Observed Coronal Structure". In collaboration with B. Schmieder and P. Demoulin we are carrying out, for the first time in over 20 years, an extensive set of magnetic field extrapolations for comparison with simultaneous high-quality coronal structure observations. Preliminary indications are that it is much more difficult to fit the observed coronal structure than had previously been thought.

OBSERVATIONS AND INTERPRETATION OF SOFT X-RAY LIMB ABSORPTION  
SEEN BY NIXT

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## Abstract

The Normal Incidence X-ray Telescope obtained a unique set of high resolution full disk solar images which were exposed simultaneously by X-rays in a passband at 63.5 Å and by visible light. The perfect alignment of a photospheric visible light image with a coronal X-ray image enables us to present observations of X-ray intensity *vs* an accurately determined height above the visible limb. The height at which the observed X-ray intensity peaks varies from 4000 km in active regions to 9000 km in quiet regions of the sun. The interpretation of the observations stems from the previously established fact that, for the coronal loops, emission in the NIXT bandpass peaks sharply just above the footpoints. Because there is *not* a sharp peak in the observed X-ray intensity *vs* off limb height, we conclude that the loop footpoints, when viewed at the limb, are obscured by absorption in chromospheric material along the line of sight. We calculate the X-ray intensity *vs* height predicted by a number of different idealizations of the solar atmosphere, and we compare these calculations with the observed X-ray intensity *vs* height. The calculations use existing coronal and chromospheric models. In order for the calculations to reproduce the observed off limb X-ray intensities, we are forced to assume an atmosphere in which the footpoints of coronal loops are interspersed along the line of sight with cooler chromospheric material extending to heights well above the loop footpoints. We argue that the absorption coefficient for NIXT X-rays by chromospheric material is roughly proportional to the neutral hydrogen density, and we estimate an average neutral hydrogen density and scale height implied by the data.

Subject headings: Sun: chromosphere - Sun: X-rays - Sun: corona

# 1 Introduction

As a result of heating by mechanisms which are still not fully understood, temperature increases with height in the solar atmosphere above the temperature minimum. Hydrogen, the primary constituent of the atmosphere, emits Lyman- $\alpha$  radiation at temperatures up to  $\sim 10^5$  K where hydrogen becomes fully ionized. The narrow transition region between  $10^4$  and  $10^5$  K has a very steep temperature gradient as consequence of the strong Lyman- $\alpha$  cooling at the lower temperatures in this range. The corona, at temperatures  $\sim 10^6$  K, occupies regions of the atmosphere above the transition region, and its mass is observed to be predominantly confined by magnetic fields to closed loop structures, while much of the volume of the corona contains low density plasma in open magnetic field structures. The chromosphere, at temperatures  $\sim 10^4$  K and below, occupies the lower regions of the atmosphere, and it includes magnetically confined structures such as spicules and loops, as well as a diffuse component. While the atmosphere may generally be thought to consist of a hot corona which exists above a cool chromosphere, the NIXT data indicates that some of the cool plasma extends up to heights a few thousand kilometers above the base of coronal structures.

The Normal Incidence X-ray Telescope (NIXT) (Golub, *et al.* 1990) obtained a set of full disk solar images which were exposed simultaneously in both soft X-rays and the visible continuum. The NIXT main telescope operates at prime focus, using a multilayer-coated 27.5 cm diameter primary mirror designed to reflect X-rays in a passband around 63.5 Å. Since the primary also reflects visible light, the visible and X-ray images were in complete alignment on the same negative at the same time. This allows for a unique opportunity to establish the spatial relations between photospheric and coronal (X-ray) features. These photos show a dark circular band off the limb, between the photosphere and lower corona (figure 1). The inner edge of this dark band results from the rapid limb darkening of the visible light contribution to the image, and it allows us to determine

the height of X-ray intensities observed off the limb. The outer edge is X-ray brightening due to line of sight effects, and we will show that these effects result from a combination of X-ray emission processes in coronal material and X-ray absorption processes in chromospheric material.

The NIXT passband includes lines from a number of coronal ions, which allows it to observe plasma at temperatures of around  $10^6\text{K}$  and higher (*i.e.*, the lower corona). In NIXT observations on the disk, many coronal loops are characterized by very bright, low lying regions just above the loop footpoints. Using a hydrostatic loop model, Peres, Reale, & Golub (1993) showed that this feature is a result of the steep temperature gradient through the transition region at the base of the loop, and the sensitivity of the NIXT bandpass to low coronal temperatures. The photospheric image in the 1991 February data allows us to examine X-ray intensities off the disk as a function of height above the visible limb. From examining this data, we know that the bright loop footpoints are not observed just off the disk at the limb, because there are no bright structures seen low in the atmosphere above the limb. Coronal plasma is generally optically thin to X-rays in the NIXT passband, while material at chromospheric temperatures readily absorbs these X-rays. Therefore, it seems most likely that the reason these loop footpoints are not seen at the limb is that they are obscured by absorption in chromospheric material in the foreground which extends to heights above the loop footpoints. We believe this absorption is due almost entirely to photoionization of hydrogen and helium. As a result, the NIXT can data provide information on the line of sight density of plasma at chromospheric temperatures.

Section 2 describes the data and data reduction. The data set consists of radial scans taken across the limb in one of the 1991 February NIXT images. Each scan yields a measurement of X-ray intensity *vs* height above the visible limb. In section 3, we discuss the physical processes in the solar atmosphere which affect X-rays in the NIXT bandpass, and in section 4, we summarize the observed X-ray intensity *vs* height above the visible limb for radial scans taken at all angles around the solar disk. In section 5, we compute the expected NIXT X-ray intensity *vs* height above the visible limb for various



idealizations of the solar atmosphere. We conclude that the best explanation for the NIXT data is that chromospheric and coronal material intermingle throughout a range of heights in the atmosphere. We then obtain a rough estimate of the chromospheric mass *vs* height in the solar atmosphere above 3000 km. In section 6, we discuss this estimate in the context of past and future observations of the solar atmosphere.

## 2 Data and Reduction

### 2.1 NIXT Photographs - 1991 February Flight

For the flight of 1991 February 22, the main NIXT telescope was a Newtonian with a 27.5 cm diameter  $\sim f/8$  primary mirror, coated with multiple Co-C layers so that it would reflect soft X-rays at normal incidence. (Spiller, *et al.* 1991) Although the theoretical resolution of the telescope for X-rays, as measured interferometrically before launch, was around 0.05 arc seconds, the  $9\mu\text{m}$  RMS granularity of the 70mm Kodak Tech Pan film, which was used as a detector, limited the spatial resolution to just under 1 arcsec, or  $\sim 600$  km on the sun. The scattering of the multilayer mirror is the lowest ever seen in an X-ray telescope, and was estimated from the 1991 July flight data to be down by a factor of 2000 at 3 arcsec (Spiller, *etal.* 1992). Furthermore, the film used has an "anti-halation" backing which prevents light spreading in the film itself, as is best demonstrated by the high contrast in NIXT images of a flare observed behind the limb on 1989 September 11 (Herant, *et al.* 1991). In order to avoid defocus of the telescope, the entrance aperture was covered with a thin aluminized Lexan heat rejecting prefilter designed to block out approximately 2 orders of magnitude of visible light while being relatively transparent to soft X-rays. In addition, a thin filter of layered carbon and pthalocyanene was located directly in front of the detector assembly to provide an additional nine orders of magnitude of visible light rejection. The thickness of the carbon filter was determined by the criterion that, in the event of a prefilter failure, only the longest exposure images would have a significant visible light contribution. The multilayer mirror had a reflectivity of about

30% for visible light and about 6% at 63.5 Å. The NIXT is described in detail in Spiller, *et al.* (1991).

On 1991 February 22, the NIXT was launched on a NASA sounding rocket from White Sands Missile Range and obtained a sequence of images from 19:47 to 19:52 UT, with exposure durations equal to 1, 3, 10, 30 and 60 seconds. Examination of the images indicates that some sections of the prefilter broke during the launch, and part of the mirror was exposed to visible light. The visible image only shows up on the longer exposures because (1) the contrast of Kodak Tech Pan Film is much higher in visible light than in soft X-rays, (2) the film experiences reciprocity failure for exposure to visible light, but not to X-rays, and (3) the thickness of the carbon filter was selected with the criteria mentioned above.

For analysis purposes, the images were enlarged and then digitized with a microdensitometer using a pixel size which corresponds to .59 arcsec, or 421 km on the sun. The film was calibrated by exposure to a 67.6 Å source, giving energy both in terms of photographic density, and in terms of densitometer units. The calibration was then refined by comparing flight film images with different exposure times and taking advantage of the fact that there is no reciprocity failure for exposure to X-rays. The details of the X-ray energy calibration will be published in a future paper.

To analyze the dark band seen around the limb in the NIXT photographs, radial scans were taken across the limb at all angles around the solar disk. The scans were spaced at one degree intervals, each scan encompassing a wedge two degrees wide. Each radial scan consists of a set of X-ray intensity values averaged over two degree arcs at a set of fixed distances from disk center. Two typical scans are shown in figure 2. The visible light contribution is used for locating the limb. This location process, described in the next section, establishes the height scale (*i.e.*, the horizontal axes in figure 2) for the X-ray intensities observed off limb. On the disk, the film is exposed to both X-rays and visible light, so that the X-ray intensity values are obviously not quantitatively meaningful there. Thus, once the visible limb has been accurately located, we discard the on disk portion of the radial scans and present observations of X-ray intensity *vs* height above

the visible limb.

## 2.2 Visible Light Calibration/Location of the Visible Limb

The 1991 February NIXT data permits, for the first time, a precise location of the visible limb on a high resolution X-ray image. The NIXT images are recorded in terms of densitometer units that need to be converted to visible light intensity in order to make comparisons with previous measurements. Thus, a visible light calibration is required, but its accuracy is important only in so far as it affects the location of the limb. Furthermore, while the image of the photosphere is most pronounced on the 60 second exposure NIXT images, there are very few areas on the limb where the X-ray contribution to the film exposure can be considered negligible relative to the visible light contribution. Thus, the method of locating the visible limb must account for this X-ray 'contamination'. In this section, we will: (1) describe the visible light calibration, (2) estimate the NIXT visible light spatial resolution, (3) describe numerical studies using previous measurements to show that the visible limb can be located by finding the knee and inflection point in radial scans across the limb, and (4) apply this method to locate the visible limb on the NIXT data.

We obtained a visible light calibration by the following procedure: The relationship between densitometer units and visible light intensity was determined over a narrow dynamic range for two images, a 30 and a 60 second exposure, by comparing densitometer units from the NIXT flight data with the known limb darkening function from  $.9R_{\odot}$  ( $\mu=.44$ ) to  $.98R_{\odot}$  ( $\mu=.2$ ) in a region near the south pole where the X-ray contribution to the film exposure was minimal. The wavelength of the visible light was taken to be  $\sim 6800\text{\AA}$ , based on the combined response of the Luxel filter and the film. The particular 30 second exposure image was selected because it was recorded during the rocket's atmospheric re-entry, leading to an X-ray attenuation by a factor of 2.5, but not a defocus of the telescope. For a more complete calibration, the reciprocity failure between 30 and 60 sec exposures was then estimated as  $\text{Log}_{10}(\Delta \text{ Exposure})=-0.16$ , so

that the 60 sec calibration could be extended to include the dynamic range of visible light at the extreme limb. The resulting calibration was consistent with Kodak Tech Pan specifications. As will be seen later, the limb location yields the same results regardless of whether the X-ray calibration or the visible light calibration is used, and so we will conclude that the limb location is insensitive to errors in the visible light calibration.

The NIXT visible light spatial resolution was estimated by comparing a sunspot region on a 60 second exposure NIXT image with the convolution of different width gaussians and a higher resolution image of the same sunspot region taken at Big Bear Solar Observatory, 19:48 UT. This yields an estimated visible light resolution of 2 to 2.5 arcseconds FWHM.

A common reference level in the photosphere is the height at which the radial optical depth in the continuum at 5000 Å is unity ( $\tau_{5000}=1$ ). The height of the visible limb has been determined by Weart & Faller (1969) as the inflection point in the variation of the 6404 Å intensity across the limb observed during a solar eclipse. They find that this height is 240 km above the  $\tau_{5000}=1$  level in the photosphere. We adopt the Weart & Faller visible limb position as the  $h=0$  point of our height scale. The convolution of the known visible intensity variation across the limb with the NIXT spatial resolution for visible light can be compared with radial scans of the NIXT data across the limb to locate  $h=0$  in the NIXT data, but we must account for the fact that the film exposure is due to both X-rays and continuum light.

We use the Weart and Faller data combined with the on disk limb darkening function from Allen (1976) to carry out numerical simulations of NIXT radial scans by convolving the visible light intensity with various gaussian resolutions, and using a sampling frequency of 100 km. One such convolution is shown in figure 3. The results display a knee (point of the most negative second derivative) and point of maximum downward slope (inflection point). We determined the location of the limb relative to these points and found that the distance between the knee and the point of maximum downward slope is an approximately linear function of the resolution. The visible limb is always near the point of maximum downward slope, and its location relative to this point is only a slowly

varying function of resolution (*e.g.*, for a visible light resolution of 450 km FWHM, the distance between  $h=0$  and the point of maximum downward slope is less than the 100 km sampling resolution of the numerical studies, while for a resolution of 2200 km FWHM, the limb is some 200 km above it.) To simulate the effect of X-ray 'contamination', we added polynomials resembling the observed X-ray limb brightening to the numerical studies. We found that neither the knee nor the inflection point changed. Not only is this method of locating the limb resilient to uncertainties in the visible light resolution and the X-ray contribution to the film exposure, but the distance between the knee and inflection point provides an independent estimate of the resolution.

We applied this method to a 60 sec NIXT image, taking 360 radial scans two degrees wide around the limb in one degree steps, using both the visible light and X-ray intensity calibrations. We determined the knee and inflection point in nearly all the radial scans, except for those with the highest X-ray intensities. Then we applied the results of the numerical studies described above for locating the visible limb in individual radial scans. The location of the limb for all angles around the sun revealed slight distortions of the image, probably introduced during the enlargement process. Nevertheless, by fitting a circle to these points we determined the solar radius to be  $1653 \pm 1$  pixels, thereby establishing the pixel size to better than one part in  $10^3$ . This process also locates disk center to better than half a pixel. Once  $R_{\odot}$  was determined in pixel units, the visible limb was defined as  $R_{\odot}$  from disk center.

Although this limb location was done with the visible calibration, it should be noted that the results are essentially the same even if the X-ray calibration is used : the difference in position of the inflection point using the X-ray calibration rather than the visible calibration is  $-30\text{km} \pm 270\text{km}$  for all the scans where the visible calibration is usable, while the shift in the knee is  $18\text{km} \pm 390\text{km}$ . Therefore, this method is not sensitive to errors in the energy calibration. Recall that the pixel size is 421km.

The mean distance measured from the knee to the point of maximum downward slope in radial scans across the limb was 860 km. From the results of the numerical studies described above, this distance indicates that the NIXT visible light resolution

is about 1800 km FWHM, and that the visible limb is some 100 km above the point of maximum downward slope (figure 3). A resolution of 1800 km corresponds to an angular resolution of 2.5 arcseconds, in complete agreement with the estimate above, made by comparing the NIXT data with Big Bear data.

The location of the visible limb enables us to present observations of X-ray intensity *vs* height above the visible limb. These observations are taken directly from the radial scans, and four such scans are shown in figure 4.

### 3 The NIXT Bandpass

To observe the middle and lower corona, the NIXT bandpass was chosen to include two lines of Fe XVI, whose temperature of maximum formation is  $\sim 3 \times 10^6$  K, and a number of lines of coronal ions whose temperatures of maximum formation are around  $10^6$  K. The bandpass is centered at 63.5 Å with a FWHM bandwidth of 0.9 Å.

For the X-ray emissivity as a function of temperature, we relied primarily upon the theoretical X-ray spectra of hot, optically thin plasmas computed by Raymond, Brickhouse and Smith. (Brickhouse, Raymond, & Smith 1994, Raymond 1988, Raymond & Smith 1977) Emissivity in this bandpass is dominated by collisional excitation of the lines mentioned above, except that at temperatures above about  $10^7$  K, bremsstrahlung radiation begins to dominate soft X-ray emissivity. Thus, emissivity in the NIXT bandpass rises rapidly with temperature just below  $10^6$  K, and has a weaker temperature dependence above this point, as seen in figure 6. This figure shows the coronal plasma emissivity filtered through the NIXT mirror reflectivity. The existence of many lines in the bandpass with similar temperature dependence makes the NIXT emissivity relatively insensitive to uncertainties in both the individual line emissivities and the mirror reflectivity. Line emissivities typically have an uncertainty of about a factor of two, and an uncertainty of about a tenth of a decade in their temperature (in K) of maximum strength, although the Iron lines have recently been calculated with greater certainty



(Brickhouse, *et al.* 1994).

In this paper, we define emission as the power per unit volume radiated in the NIXT bandpass, given by  $G(T) \times N_e^2$ , where  $N_e$  is the electron density, and  $G(T)$  is the emissivity shown in figure 6. The NIXT data has been calibrated in film exposure units of ergs/cm<sup>2</sup> on the flight film negative. Thus, to calculate the expected exposure from optically thin coronal emission, we use the equation

$$\text{NIXT X-ray exposure} = t \times \Gamma \times \Delta A \times \frac{\Omega}{4\pi} \times \int G(T) N_e^2 dl \equiv \alpha \int G(T) N_e^2 dl, \quad (1)$$

where  $t$  is the exposure time of the image,  $\Gamma = 60\% \times 30\% = 18\%$  is the transmission of the NIXT filters,  $\Delta A \approx R_\odot^2$  is the area on the sun which focusses to 1 cm<sup>2</sup> on the negative,  $\Omega \approx 420\text{cm}^2/\text{AU}^2$  is the heliocentric solid angle subtended by NIXT,  $dl$  is length along the line of sight, and  $\alpha \approx 0.008\text{cm}^2\text{s}$  for a 60 second exposure from the 1991 February flight. This equation yields the energy deposited per cm<sup>2</sup> on the flight film negative.

We can justify the optically thin assumption by examining the NIXT data itself. For all the NIXT flights, observations on the disk clearly indicate that the lines in the NIXT bandpass are optically thin, because X-ray bright points and coronal loops are regularly seen behind coronal loops in the foreground. For the active regions off limb, perhaps the most striking evidence that the observed NIXT emission is optically thin is the fact that the dark band (and therefore the off limb X-ray brightening) can be seen through active region loops in the foreground whose footpoints are on the disk. Specifically, the dark band is observed through the foreground emission of the extended active region at  $\sim 200^\circ$  and through the coronal loops at  $\sim 35^\circ$  in figure 1.

We note that another fact revealed by NIXT observations on the disk is that the brightest portion of active region loops generally occurs in a low lying, vertically thin region just above the loop footpoints (Peres, *et al.* 1993). These bright footpoints are hard to see in figure 1 because of the visible light contribution to the image, and because the contrast in the figure was chosen to reveal the faint features of the dark band, at the expense of poor contrast in the on disk active regions. Nevertheless, bright loop

footpoints can be seen, *e.g.*, at the base of the coronal loops near the limb at  $\sim 35^\circ$  in figure 1. We also note that  $H\alpha$  observations reveal that structures at chromospheric temperatures commonly rise to heights of 7000 km and higher (*e.g.*, Athay 1976), which is well above the coronal loop footpoints. As discussed below, this chromospheric mass can absorb NIXT X-rays. If hot and cool plasma intermingle throughout a range of heights, then the pathlengths along the line of sight through both the coronal emission and through this cooler, denser material become long for observations just above the visible limb. We will show that this intermingling can account for the fact that NIXT does not see loop footpoints when viewed above the limb.

Although the lines in the NIXT bandpass are generally optically thin in the corona, photoelectric absorption by hydrogen and helium in cooler material can contribute significantly to opacity at 63.5 Å (195eV). The photoelectric absorption cross sections by H I, He I and He II are  $\sigma_{HI} = 2.4 \times 10^{-21}$ ,  $\sigma_{HeI} = 6 \times 10^{-20}$  and  $\sigma_{HeII} = 4 \times 10^{-20}$  cm<sup>2</sup>. (Henke 1982, Osterbrock 1989) We define the optical depth due to cool plasma photoelectric absorption:

$$\tau_{abs} = \sigma_{HI}N_{HI} + \sigma_{HeI}N_{HeI} + \sigma_{HeII}N_{HeII}, \quad (2)$$

where  $N_{HI}$  is the column density of neutral hydrogen between the X-ray source and the observer,  $N_{HeI}$  is the column density of neutral helium, and  $N_{HeII}$  is the column density of singly ionized helium. Thus, equation (1) becomes:

$$\text{exposure} = \alpha \int G(T) N_e^2 e^{-\tau_{abs}} dl, \quad (3)$$

where  $G(T)$ ,  $N_e^2$  and  $\tau_{abs}$  can all vary along the line of sight,  $l$ .

We do not include the heavier elements because: (1) even the next most abundant element, oxygen, is more than a hundred times less abundant than helium, and (2) the cross sections of the first few ionization stages of the next most abundant elements are all less than that of helium. Note that the absorption cross section of singly ionized helium is only slightly less than that of neutral helium, so the ionization state of the helium has only a minor effect on NIXT X-ray absorption. Appreciable densities of hydrogen and

helium atoms exist only at chromospheric temperatures and below (see figure 7), while singly ionized helium (and other ionized species) exist at slightly higher temperatures, from the upper chromosphere through the transition region. However, we argue that it is a reasonable approximation to assume the ratio of hydrogen to helium is 10:1 and estimate the optical absorption depth as:

$$\tau_{abs} \approx (\sigma_{HI} + 0.1\sigma_{HeI})N_{HI} = 8.4 \times 10^{-21} \text{cm}^2 N_{HI} \quad (4)$$

The justifications for this approximation are: (1) the absorption cross sections of neutral and singly ionized helium differ by only 33%, (2) the transition region is very narrow compared to the vertical size of the chromosphere, so that absorption by He II and other ions in this region is not a significant effect for the analysis in this paper, and (3) most of the NIXT X-ray absorption occurs where the densities are higher, the temperatures are lower, and most of the helium is neutral. For example, in a recent chromospheric model which includes helium diffusion in the transition region (Fontenla, Avrett, & Loeser 1993, model A), the densities of He I and He II become equal at a height of 2240 km, where  $T \approx 10^4$ . Here, only a  $\sim 20\%$  error would be introduced into the absorption estimate by treating all the helium as neutral. Furthermore, the density of He I and He II are both  $\sim 10^9 \text{cm}^{-3}$ , which contribute a small optical depth of  $10^{-5}$  per km of pathlength through the material. At the nearby height of 2277 km, where  $T \approx 10^5$ , the density of He II has dropped to  $\sim 10^7 \text{cm}^{-3}$ , which contributes a negligible optical depth of  $4 \times 10^{-8}$  per km of pathlength through the material. Similarly, while other ions which exist at  $T \approx 10^5$  may have large absorption cross sections (e.g.,  $\sigma_{OV} = 2.6 \times 10^{-19} \text{cm}^2$  is the largest cross section by any ionization stage of C, N, or O), their contribution to the optical depth is small. These ions contribute little to the optical depth because of their low elemental abundances, in addition to the facts that plasma at  $T \approx 10^5$  has low densities and occupies narrow regions of space when compared to material at  $T \approx 10^4$  and below. Note that although equation 4 derives an absorption estimate from the hydrogen atom density, helium is actually responsible for most of this absorption.

In light of equation 3 and the approximation expressed in equation 4, it is clear

that the only information about the solar atmosphere which affects the observed X-ray intensities is: (1) the distribution of neutral hydrogen densities along the line of sight, *i.e.*, the densities of plasma with  $T \sim 10^4$  and below, and (2) the distribution of emission in the NIXT bandpass along the line of sight, which is determined by the temperature and density of plasma with temperatures greater than  $\sim 10^{5.5}$  K. We will estimate these physical parameters and use equation (3) to predict the observed X-ray intensity *vs* height in section 5.

## 4 Observed X-ray Intensity vs Height

In this section, we present observations of X-ray intensity *vs* height above the visible limb, obtained as described in sections 2.1 and 2.2. There are 360 scans, each spaced one degree apart and encompassing a wedge two degrees wide. A representative sample of these scans is shown in figure 4. For some scans, the X-ray intensity is dominated by emission from individual coronal loops which are extremely bright (*e.g.*, at  $\sim 35^\circ$  in figure 1), or dominated by absorption in individual cool plasma features (*e.g.*, the filament at  $\sim 165^\circ$ ), but the majority of the scans are characterized by a single peak at a low height above the limb. As we will explain in the next section, this majority of scans may be interpreted in terms of average properties of the local atmosphere: specifically, NIXT X-ray emission per unit volume as a function of height, and a cool plasma absorption coefficient as a function of height. To summarize the radial scans, the height off limb of maximum X-ray intensity is plotted *vs* angle around the sun for all scans where it was a useful quantity to define (figure 5). The maximum X-ray intensity off the limb is also plotted *vs* angle. Around  $70^\circ$ , the maximum X-ray intensity off limb is low enough that the peak off limb X-ray intensity becomes buried in the noise. Scans from this region are shown in figure 4. They provide an upper limit for the visible light contamination in all the scans across the limb.

The observed X-ray intensity peaks from as low as 4000 km above the limb in active regions of the sun to as high as 9000 km in quiet regions of the sun. The relationship

between coronal activity and the height of the maximum X-ray intensity is particularly noticeable all along the southern half of the limb, where the height of maximum X-ray intensity is clearly anti-correlated with the maximum X-ray intensity off limb. Because the observed X-ray intensity results from an interplay of emission processes in hot plasma and absorption processes in cool plasma, we defer discussion of this correlation until after the modelling of these processes has been explained in detail.

Consider the two bright, localized active regions on the western limb, at  $\sim 8^\circ$  and  $\sim 353^\circ$ . These are labeled A and B in figure 5, and scans from these regions may be seen in figure 4. At both active regions, there is a sharp local peak in the maximum X-ray intensity vs angle. At region B, there is a corresponding local minimum ( $\sim 4500$  km) in the height of maximum X-ray intensity vs angle, while at region A, the height of maximum X-ray intensity vs angle remains constant at  $\sim 6000$  km. By looking at the photograph (figure 1), it is clear that at point A, the coronal activity is primarily behind the limb, while at point B, the activity spans a region extending from just in front of the limb to over the limb. We assert that X-rays are observed from lower in the atmosphere at region B than at region A as a result of less intervening chromospheric material along the line of sight, but a complete analysis requires a comparison of the observed radial scans with model calculations, as described in the next section.

## 5 Model calculations

In this section, we consider various model atmospheres and calculate the X-ray intensities NIXT would observe in radial scans across the limb. These calculations will allow us to interpret the data presented in section 4.

## 5.1 A Spherically Symmetric Atmosphere

We begin by considering a spherically symmetric model atmosphere, that is, one in which density and temperature are functions of height alone. We combine results from the chromospheric model of Fontenla, *et al.* 1993 , and from the quiet sun coronal model of Gabriel 1976 to obtain the temperatures and densities for the model atmosphere shown in figure 7. This is a one-dimensional model without any cold plasma structures extending above the general chromosphere.

To calculate the NIXT X-ray intensity observed from a particular line of sight through this model atmosphere, we numerically integrate equation 3 along the line of sight. The geometry is depicted in figure 8. To compute the radial scan from this model atmosphere, we calculate the X-ray intensity as a function of height above the visible limb (*i.e.*, the height of each line of sight's closest approach to the photosphere, labeled  $h_0$  in figure 8), and convolve the resulting intensity *vs* height with a 625 km FWHM gaussian to simulate the NIXT spatial resolution for X-rays. The dotted line in figure 9 shows the resulting radial scan, as calculated using the model atmosphere shown in figure 7. The solid line in figure 9 shows the observed radial scan at  $55^\circ$ , a scan which is typical of those in the quiet sun.

It is clear from figure 9 that the calculation described above does not compare favorably with the observations. Note that the X-ray intensity *vs* height predicted by this spherically symmetric model atmosphere has a peak at a height of 3000 km, far below the peak in any of the quiet sun observations. More importantly, the rise in X-ray intensity at heights below the peak is much steeper in the model calculation than it is in the observations. Simply put, there is a sharp peak in X-ray intensity *vs* height near the base of the corona, which is predicted by the model, but is not observed in the NIXT data.

In section 3, we explained that optically thin emission of NIXT X-rays occurs in coronal plasma with temperatures greater than  $\sim 10^{5.5}$ , while photoelectric absorption of these X-rays occurs in cool plasma with temperatures of  $\sim 10^4$  and below. Thus, in a model atmosphere where temperature increases monotonically with height from chromo-



spheric to coronal temperatures (*e.g.*, the one shown in figure 7), NIXT X-ray absorption occurs only at heights below the material that emits the X-rays. Therefore, only those X-rays originating from behind the limb may experience attenuation before reaching the observer. The peak in the radial scan predicted from the spherically symmetric model atmosphere above may thus be qualitatively understood by considering the NIXT X-ray emission per unit volume as a function of height. As discussed in section 3, this emission is given by the NIXT emissivity (figure 6) times the electron density squared. In spherically symmetric models of the solar atmosphere, density decreases monotonically with height, and above some temperature minimum low in the chromosphere, temperature increases monotonically with height. Therefore, because NIXT emissivity rises rapidly with temperature to its peak value at  $T \sim 10^{5.9} \text{K}$ , emission will reach its maximum at height where the temperature is near, but below,  $\sim 10^{5.9} \text{K}$ . Since only those X-rays emitted from behind the limb can be absorbed, the observed X-ray intensity will be highest from a line of sight which has the longest pathlength through the heights in the atmosphere where emission is close to its maximum (*i.e.*, the low corona). In this calculation, the steep rise up to the maximum X-ray intensity results because : (1) The chromosphere starts to become transparent to X-rays from behind the limb, and (2) the steep temperature gradient in the chromosphere-corona transition region and the steep rise of emissivity with temperature below  $T \sim 10^{5.9} \text{K}$  result in a steep rise of emission with height. Since the sharp peak in the predicted X-ray intensity *vs* height is not observed by NIXT (see figure 9) we consider non spherically symmetric atmospheres. To emphasize this point, we note that if we double the atmospheric scale height of the model in figure 7 and compute the radial scan that would be observed from this ad hoc model (dashed line in figure 9), then the predicted height of maximum X-ray intensity (now  $\sim 6000 \text{ km}$  off limb) agrees with much of the data, but the sharp rise to the peak in X-ray intensity still leads to a poor agreement between the radial scans from the model and from the data.

## 5.2 An Atmosphere Without Spherical Symmetry

We now consider the more general case in which the transition region can occur at different heights for different locations on the sun, or in which the line of sight passes through cool chromospheric material (*e.g.*, spicules) that extends up into the corona. The effect of the transition region occurring at different heights for different locations is that the sharp peak in observed X-ray intensity *vs* height will become less pronounced than it is in the calculations above because (1) the height of maximum X-ray emission now has a spread of values, and (2) chromospheric plasma in some regions can occupy heights above the lower corona of other regions. We will show later that the NIXT off limb observations are consistent with an atmosphere in which the peak in coronal emission is obscured by chromospheric absorption along the line of sight.

XUV imaging observations have revealed that coronal plasma is clearly not spherically symmetric, but is predominantly confined by magnetic fields in structures known as coronal loops (*e.g.*, see figure 1). Therefore, in considering NIXT X-ray emission in an atmosphere without spherical symmetry, we consider the emission in individual coronal loops. We expect a sharp peak in emission near the base of coronal structures, just as in the spherically symmetric case above. In fact, NIXT observations of active regions on the disk reveal areas of intense emission at the footpoints of coronal loops. Peres, *et al.* (1993) explain these observations by using a hydrostatic coronal loop model, and they show that emission of X-rays in the NIXT bandpass will peak sharply just above the base of high pressure loops. This model assumes a semicircular loop geometry and constant cross section. Setting the base of the loop at 1300 km above the photosphere with  $T=2\times 10^4\text{K}$ , Peres, *et al.* (1993) computed models for a variety of loop lengths and base pressures. The loop length and base pressure are the only two independent parameters required to characterize the loop ; for instance, the maximum plasma temperature, which occurs at the loop apex, is related to these two quantities by a scaling law. Peres, *et al.* (1993) found that, near the loop base, emission as a function of distance from the base of the loop is not dependent on the length of the loop. Thus, the peak in emission near the base of the loop is characterized by the pressure alone. The relevant results of

the model, namely temperature, density and emission vs. arclength, are plotted in figure 10 for a loop base pressure typical of an active region and one typical of the quiet sun. In active regions, where the loop pressures and peak temperatures are high, a temperature of  $\sim 10^{5.9}\text{K}$  (where NIXT emissivity attains its maximum) is reached just barely above the base of the loop, where the temperature gradient is still very steep, so a sharp peak in emission occurs at the base of the loop. In quieter regions of the sun, loops do not reach as high a temperature, so  $T \sim 10^{5.9}\text{K}$  occurs further above the transition region, and a broader and not as bright peak in emission occurs higher in the atmosphere.

We now turn to the question of incorporating this model (Peres, *et al.* 1993) in computations to predict the observed NIXT X-ray intensity *vs* height from a horizontally structured solar atmosphere. As before, we need to integrate equation 3 along lines of sight above the visible limb. The fact that the radial scans are averaged over two degree wedges, combined with line of sight effects (all the data is from lines of sight just above the visible limb), implies that any one radial scan will include many individual chromospheric and coronal features. Therefore, we integrate equation 3 using two horizontally averaged properties of the local atmosphere, namely, the average emission per unit volume, and the average photoelectric absorption coefficient per unit length, both as a function of height. This integration is depicted in figure 11. In this context, 'average' quantity means the value of the quantity at a given height, averaged over all regions encompassed by a given radial scan. By performing the integrations using these average quantities, we are able to express the intermingling of plasma at chromospheric and coronal temperatures through a range of heights in the atmosphere: the average absorption coefficient does not fall to zero at a height below the rise of coronal emission, as it does in the spherically symmetric case above.

To obtain the average emission per unit volume *vs* height using the Peres loop model, we make some simplifying assumptions about the corona. First, we assume that all loops within a radial scan have the same pressure. While this is extremely unlikely, it allows us to explore the effect of varying the pressure without the additional complications of determining a distribution of loop base pressures. Secondly, we obtain emission *vs* height

for the loops by taking the emission *vs* arclength for a loop with semi length of 100,000 km, and we assume that arclength along the loop from the photosphere is equivalent to height in the solar atmosphere. This assumption is obviously invalid near the loop apex, but is nevertheless justified here because : (1) we will only use the resulting emission *vs* height to compute the observed X-ray intensity from lines of sight just above the visible limb (only the results from 3000 to 10,000 km off limb will be used in the final analysis). (2) Since emission falls with height above the loop footpoints (it falls roughly as the electron density squared), emission high in the atmosphere does not significantly affect X-ray intensities observed just above the limb. Note that, in these calculations, there is no emission at heights above 100,000 km if a loop semi length of 100,000 km is used. To explore the effects of using various semi-lengths, we computed radial scans from 0 to 20,000 km off limb. These computed radial scans assumed an emission *vs* height as described above, except that the calculations were done using a loop semi length of 50,000 and 500,000 km as well as 100,000 km. The scans were calculated for a variety of loop base pressures, varying from 0.05 to 3 dynes/cm<sup>2</sup>, and with no chromospheric absorption. The variation of the loop semi length did not significantly affect the resulting radial scans for any of the loop pressures. Therefore, it is clear that for computing X-ray intensities just above the limb, none of the emission at heights above 50,000 km is important. A third implicit assumption is that below all the loop footpoints,  $T=2\times 10^4\text{K}$  at height of 1300 km, an assumption of the loop model itself. We will call the height in the loop where  $T=2\times 10^4\text{K}$  occurs the loop base height, and will explore the variation of this parameter as well. Finally, we note that, to obtain the average emission per unit volume *vs* height from the loop emission *vs* height, in this simple model, we merely need to multiply by a loop filling factor. Thus, we have a simple coronal 'model' with three independent parameters : loop base pressure, loop base height, and loop filling factor. This simple model is a useful tool for interpreting the NIXT radial scans, and is intended for use only in this context.

To calculate the 'observed' X-ray intensities from the coronal model above, we would also need to specify the average absorption coefficient for NIXT X-rays that is assumed to

result from photoionization of material at chromospheric temperatures. This coefficient is roughly proportional to the average neutral hydrogen density, as discussed in section 3. Alternatively, we can obtain an estimate of the neutral hydrogen density from the NIXT data by using the model described above. It should be clear from the outset that any absorption estimate from the NIXT data will not give a precision measurement, primarily because the total emission along the line of sight is unmeasurable if some of it is absorbed. We note that even if the distribution of emission along all lines of sight were known for a given radial scan, the observed X-ray intensities would not unequivocally locate the absorption along the line of sight. With these facts in mind, we devised the method described below to estimate the distribution(s) of average neutral hydrogen density *vs* height which are consistent with the NIXT data.

### 5.3 Estimating Chromospheric Density *vs* Height

Recall that models of high pressure coronal loops and NIXT observations of such loops on the disk indicate a bright peak in emission just above the loop footpoints (Peres, *etal.* 1993), but that a correspondingly bright peak in the observed X-ray intensity *vs* height off limb is not seen by NIXT. Also, the NIXT X-ray intensity generally peaks at around 6000 km above the limb, well above the expected height of loop footpoints. This inconsistency can be explained if the loop footpoints viewed at the limb are buried by absorption in chromospheric material along the line of sight. In light of the difficulties mentioned above in estimating the chromospheric mass responsible for this absorption, we will assume that the average neutral hydrogen density has the simple dependence  $N_H = N_H(0)e^{-h/h_H}$  at the heights the NIXT data is sensitive to, where  $h_H$  is the neutral hydrogen density scale height, and  $N_H(0)$  is the density extrapolated to a height of 0 km. By combining this 'model' with the coronal model described above, we can then perform a least squares fit to the data to determine the two parameters which characterize the neutral hydrogen density. But first, let us summarize our adopted process of computing radial scans.

We predict the observed X-ray intensities above the limb from a theoretical atmo-

sphere with five input parameters : (1) coronal loop base pressure, (2) coronal loop base height, (3) coronal loop filling factor, (4) average neutral hydrogen density scale height, and (5) average neutral hydrogen density at some specified height. The first two parameters determine the coronal emission *vs* height, and multiplying this emission by the filling factor yields the average emission *vs* height. The last two parameters determine the average NIXT X-ray absorption coefficient *vs* height. Equation 3 can then be integrated along different lines of sight, as depicted in figure 11, to obtain the observed X-ray intensity *vs* height above the visible limb, and finally, we convolve the resulting intensity *vs* height with the NIXT resolution to obtain a predicted radial scan. For the sake of brevity, we will refer to such a prediction from this five parameter atmosphere as a 'model scan'.

For a given NIXT radial scan, we can obtain a best fit of the model scan to the data by minimizing the sum of the fractional squared errors with respect to variations in all the parameters. In other words, for a set of observed NIXT X-ray intensities  $\{I_i\}$  at heights  $\{h_i\}$  above the visible limb, we minimize  $\Sigma(I_i - I(h_i))^2/I_i^2$ , where  $I(h)$  is the intensity *vs* height predicted by the model scan, and is a function of the five parameters mentioned above. However, because our objective is to estimate the two neutral hydrogen density parameters, and because of the computational burden of the problem, we chose to treat the first two parameters (loop pressure and base height) as fixed, and minimize the sum of the errors squared with respect to the last three parameters (loop filling factor, neutral hydrogen scale height, and neutral hydrogen density), for a set of values of loop pressure and base height. We chose the set of loop pressures to be  $\{0.05, 0.07, 0.1, 0.15, 0.2, 0.3, 0.5, 0.7, 1, 1.5, 2, 3, 5\}$  dynes/cm<sup>2</sup> in order to sample a physically reasonable set of pressures ranging from quiet to active regions of the sun, and we chose the set of loop base heights to be 1300, 2000 and 2700 km. Thus, we obtain a set of neutral hydrogen densities and scale heights which provide the best fit to the data for a variety of reasonable coronal emission *vs* height functions. In this way, we are able to gauge the uncertainty that our lack of knowledge about the coronal emission *vs* height introduces into our estimate of the two neutral hydrogen density parameters. The simplifying assumptions



of our theoretical corona, *e.g.*, that loops are evenly distributed all along the limb, must also introduce uncertainty into the NIXT neutral hydrogen density estimate, and this can be gauged by obtaining results from as many different regions of the sun as possible. We now discuss the fitting process and its results in more detail.

Before fitting model scans to the data, we decided to average adjacent radial scans to obtain a better signal to noise ratio. Where possible, we selected regions of the sun where the X-ray intensity *vs* height did not change very much from one scan to the next, and averaged 5 scans  $2^\circ$  apart to obtain a radial scan for a  $10^\circ$  wedge. In active regions, such regions were more difficult to find, and in some cases we only averaged 4 scans, forming an  $8^\circ$  wedge. Because of the model scan's assumption that coronal emission is evenly distributed over the sun's surface at the limb, we limited the selection to regions where this assumption was at least somewhat plausible. Fortunately, there are some large extended active regions which are not obviously dominated by emission from individual coronal loops. The 19 regions selected may be seen in figure 12. For each of these 19 regions, we fit model scans to the observed X-ray intensity *vs* height from 3000 km to 10,000 km above the limb. That is, for 39 sets of values of base pressure and base height (13 pressure values times 3 base height values, as given in the previous paragraph), we minimized the sum of the fractional squared errors to find the values of three parameters, neutral hydrogen density, scale height, and coronal loop filling factor, which fit the data best. Only data more than 3000 km above the visible limb was used because the film's exposure to visible light could be ignored above this point (see figure 4). In order for the coronal filling factor to be uncorelated with the chromospheric density parameters, data must be included at heights above those where chromospheric absorption is significant, and this is why we chose to use the data out to 10,000 km. Including data from greater heights would not help to constrain the chromospheric density parameters, and the assumptions of the model scan are invalid at large heights because of the loops' curvature. For a number of regions of the sun, we also fit the model scan to the data in other ranges, from 4000 km to 10,000 km, and from 3000 km to 12,500 km. In some cases, the resulting chromospheric density parameters from these fits differed by as much as 10% relative to

the values obtained by fitting to the data from our standard 3000 km to 10,000 km.

To locate the minimum of the sum of the fractional squared errors, both a simplex method and a gradient search method were employed. In all cases where a convergent solution was found, the two methods located the same minimum. Of the three parameters found, neutral hydrogen density, scale height, and coronal loop filling factor, we are interested primarily in the first two. The loop filling factor is highly dependent upon the assumed loop base pressure, and is also subject to uncertainties in the absolute calibration of the NIXT instrument. Because the neutral hydrogen density and scale height are determined from the relative absorption effects, they do not depend upon exact knowledge of NIXT's effective collecting area. The uncertainties in the neutral hydrogen parameters, as determined by contours of the total squared errors function in the two dimensional space spanned by these two parameters, were much less than the systematic uncertainties introduced by the assumptions of the model scan. We have tried to estimate the latter uncertainties by performing the fit to 19 different regions of the sun, using the 39 different sets of coronal loop parameters, and then observing the statistical spread in the resulting parameter values. However, the model scan does not provide a good fit to the data for all the cases studied, so we adopted the following selection criteria to obtain a set of reasonable fits which could be used to estimate the neutral hydrogen density and scale height implied by the NIXT data: (1) The RMS percent error of the fit must be less than 1%. (2) The coronal loop filling factor must be less than 10%, except for the two lowest loop pressures studied, 0.05 and 0.07 dynes/cm<sup>2</sup>, where we allowed fits with filling factors of up to 25%. The reason for this exception is to include more fits from the quiet sun regions, because otherwise our sample would be heavily biased towards active region results. (3) For scans where the maximum X-ray intensity was less than  $5 \times 10^{-2}$  ergs/cm<sup>2</sup>, (i.e., quiet sun regions), we did not include fits with a loop base pressure greater than 0.5 dynes/cm<sup>2</sup>, as this is not physically probable. (4) Six fits were excluded because the filling factor values were found to be correlated with the other two parameters. 131 fits pass these selection criteria. In figure 12, we present the NIXT data from the 19 selected regions of the sun, along with some of the corresponding model

scans. For each region, we show the fit which passed the above criteria with the lowest RMS error (solid lines), and the fit which passed with the highest RMS error (dotted lines). We also report the five parameters for each model scan displayed. The neutral hydrogen density parameter is reported at a height of 4000 km because this is the height at which the density is best constrained by the NIXT data.

The above set of model scan fits is intended for the sole purpose of estimating the two neutral hydrogen density parameters for a set of physically reasonable coronal emission *vs* height functions, and for a variety of locations around the sun. The resulting distribution of these two parameters, which may be seen in figure 13, then yields an estimate as to how well the NIXT data constrains the average neutral hydrogen density above 3000 km. Both the average neutral hydrogen density at 4000 km and the scale height have distributions which span about an order of magnitude (figure 13). Thus, the estimates of these parameters may have an order of magnitude uncertainty. In figure 13, we also show the distributions of coronal loop base pressures and base heights, which determine the coronal emission *vs* height, and the distribution of the maximum NIXT X-ray intensity observed off the limb, for the set of selected fits. To emphasize the correlation between the assumed loop base pressure and the neutral hydrogen scale height resulting from our fits, we have shaded the portions of these distributions for which the pressure was  $0.7 \text{ dynes/cm}^2$  or less. Thus, it becomes clear from figure 13 that, generally speaking, lower pressures give longer scale heights, while higher pressures give shorter scale heights. Qualitatively, one reason for this correlation is that the higher pressure loops have a brighter peak closer to their base, thus 'requiring' more absorption lower in the atmosphere in order to mimic the NIXT radial scans. Although the lower pressure fits are generally for the data with a lower X-ray intensity (i.e., the quiet sun), it is inappropriate to conclude from the correlation between pressure and scale height that the hydrogen scale height is longer in quiet sun regions, because this correlation holds for different fits to the same region of the sun. The spread in scale heights resulting from this correlation merely indicates part of the uncertainty which our lack of knowledge about the coronal emission along the line of sight introduces into our chromospheric mass estimate. While the variation of the neutral

hydrogen scale height from quiet to active regions of the sun is certainly an interesting question, our estimates are not accurate enough to explore this variation.

Another source of uncertainty in our neutral hydrogen density estimate results from lack of knowledge about the coronal emission distribution, and specifically from the assumption that the coronal material filling factor is constant. If there is more emission behind rather than in front of the limb, then, for the same neutral hydrogen distribution, there will be more absorption of the NIXT X-rays and there will be a steeper initial rise in the X-ray intensity *vs* height. This will lead to artificially low estimates of the hydrogen scale height. Conversely, more emission in front of rather than behind the limb will lead to the opposite. We have tried to incorporate this uncertainty into our estimate by fitting our model scan to 19 different regions of the sun.

Finally, we note that while NIXT observations of bright loop footpoints on the disk combined with the absence of a bright peak in X-ray intensity *vs* height off limb led us to suggest that coronal and chromospheric material intermingle throughout a range of heights in the atmosphere, the densities derived by the method above depend primarily upon the NIXT X-ray emission *above* the loop footpoints. This is because we only use the data more than 3000 km above the visible limb. In the observations, the bright footpoints appear to be completely obscured by cool plasma in the foreground. But, in some of the model scan calculations, the bright footpoints can be seen 'peeking through' the absorption. For instance, in figure 12, the model scan (solid line) shown for the region  $200^\circ$  to  $210^\circ$  exhibits a local maximum in X-ray intensity below 3000 km, a feature not seen in the data (solid squares and open diamonds). Above 3000 km, both the data and the model scan rise to a maximum X-ray intensity at  $\sim 5000$  km. However, because it is below 3000 km, this feature of the calculations does not affect any of the results of the fits. Furthermore, it is most likely an artifact of two assumptions of the model scan. First, the model scan assumes the same base height for all coronal loops. Relaxation of this assumption would spread the emission from the bright footpoints over a range of heights. Secondly, the optically thin assumption (from section 3) is questionable for a line of sight passing horizontally through a number of bright footpoints, especially since

observations on the disk indicate that these bright footpoints have a greater horizontal than vertical extent.

By fitting models scans to the NIXT observations of X-ray intensity *vs* height above the visible limb, we have obtained an estimate of the average neutral hydrogen density *vs* height in the solar atmosphere. This estimate is parameterized by a density at a height of 4000 km and a density scale height. The distributions of these two parameters (figure 13) provide a fair indication of the uncertainty in the NIXT estimate, although variations amongst different regions of the atmosphere are responsible for at least some of spread in these distributions.

## 6 Discussion

In figure 14, we present the NIXT neutral hydrogen density estimate along with some estimates and predictions by other authors. For heights ranging from 3000 km to 10,000 km, we computed the average and standard deviation of the logarithm of the neutral hydrogen densities derived from all the model scan fits which passed the selection criteria described in the previous section. The resulting neutral hydrogen density *vs* height is shown by the solid line in the top plot of figure 14, while the shaded region around this line shows the standard deviation of the derived densities about the average. We consider this standard deviation to be a fair indication of the uncertainties associated with the NIXT neutral hydrogen density estimate. The actual distribution of the derived neutral hydrogen densities at a height of 4000 km may be seen in figure 13. The large uncertainty in the NIXT estimate, about an order of magnitude, results primarily from the fact that this cool mass is inferred from its absorption of NIXT X-rays. Because of this absorption, it is hard to quantify the X-ray intensities which are being absorbed, and in turn, it is hard to quantify the absorption. Nevertheless, we are certain of the existence of this absorption because NIXT observes bright coronal loop footpoints on the disk, but not off the disk just above the visible limb, where a line of sight can cross through many of these footpoints. This discrepancy can be explained by the fact that the loop footpoints,

when viewed off limb, are interspersed along the line of sight with cooler chromospheric temperature material extending to heights above the loop footpoints. The chromospheric material absorbs NIXT X-rays via photoionization of helium and hydrogen, and we argued in section 3 that this absorption is roughly proportional to the neutral hydrogen density since the majority of absorbing material has a constant hydrogen to helium ratio of 10:1. Because these heights of the solar atmosphere are characterized by an intermingling of different temperatures and densities at the same height, we choose to refer to the 'average' neutral hydrogen density in order to estimate absorption effects, where by 'average', we mean the sum of the filling factors times the hydrogen densities of all structures found at a given height.

In the bottom plot of figure 14, we show calculations of the total optical absorption depth along lines of sight through 'model' atmospheres with the four distributions of average neutral hydrogen density *vs* height shown in the top plot. That is, for each distribution of hydrogen density *vs* height, we calculated the optical thickness for tangential NIXT X-rays, considering only photoionization in cool ( $T \approx 10^4$  and below) plasma, at a number of lines of sight above the visible limb. To avoid confusion of this quantity with the total optical depth through the coronal plasma in which the X-rays originate, we refer to it as an absorption depth. Because the NIXT average neutral hydrogen density estimate is obtained from absorption effects, it is not meaningful above heights where its tangential optical absorption depth is much less than one. Thus, the uncertainty in the NIXT estimate becomes progressively larger at heights above  $\sim 5000$  km.

In addition to the NIXT estimate of the average neutral hydrogen density *vs* height, figure 14 shows other predictions and estimates of this hydrogen density *vs* height. The 'FAL' model (Fontenla, *et al.* 1994, model A, Vernazza, Avrett, & Loeser 1981) is a one-dimensional hydrostatic model of the chromosphere and transition region, shown primarily for reference. This model does not explain the X-ray absorption seen by NIXT, and it was not intended to do that. The Ewell model (Ewell, *et al.* 1993) is an empirical model derived from observations of the infrared limb. They show that, for wavelengths between  $3000 \mu\text{m}$  and  $200 \mu\text{m}$ , the dependence of limb height upon wavelength implies



an electron density scale height of 1200 km. The neutral hydrogen densities from their model then depend on assumptions about the ionization fraction of the plasma, but it is clear that the neutral hydrogen scale height should be less than the electron scale height. Model scans computed by combining the coronal model discussed in section 5 with the hydrogen densities of the Ewell model result in a rise of X-ray intensity with height off limb which is too steep to be consistent with the NIXT observations. In contrast with the gradual rise of intensity with height seen in figures 4 and 12, the predicted intensity using the Ewell model generally takes a sharp turn upwards between 3000 and 4000 km above the limb, and rapidly climbs to a peak value just above 5000 km. This fact can be surmised from the tangential optical absorption depth (lower plot in fig 14). For a line of sight passing a little more than 3000 km above the visible limb, the total absorption depth is 10, which means that less than 1% of the NIXT X-rays emitted directly above the limb at this height can reach the telescope. At 5000 km above the limb, the tangential absorption depth is 0.2, and 90% of the X-rays originating from 5000 km directly above the limb and directed towards the telescope will make it.

Lastly, we obtained a crude estimate of the average neutral hydrogen density in spicules by consulting review articles (Athay 1976, Beckers 1972) on spicular observations. Athay summarizes  $H\alpha$  observations in which the number of spicules in a given field of view were counted as a function of height off the limb. The spicular number density as a function of height in the solar atmosphere may be deduced from these observations and is tabulated in Athay 1976. Assuming that spicules have a diameter of 900 km, constant with height, the spicular number density may be converted directly into a spicular filling factor. We note that the equation  $N=4.4\times10^{11}e^{-h/4000km}cm^{-3}$  is a good representation of Beckers' "most likely spicular densities" above 3000 km, which were derived from line intensity ratios ( $h$  refers to height in the solar atmosphere). Assuming that the spicules are cool enough so that their hydrogen is primarily unionized, the filling factors from Athay times this density function then yields an estimate of the average neutral hydrogen density *vs* height in spicular material. This is the estimate shown in figure 14. Note that, at a height of 3000 km off the limb, this mass would only lead to  $\sim 25\%$

attenuation of X-rays originating from the far side of the limb, so this spicular mass cannot account for the NIXT observations. However, not all the chromospheric mass above 3000 km is confined in spicules. For instance, an interspicular medium has been observed in  $H\alpha$  (Giovanelli 1974). Furthermore, the spicule counts which form the basis of this mass estimate are most likely too low, because it is easy to undercount them due to the fine distribution of doppler shifts among different spicules (Koutchmy 1994). Thus, it is not surprising that this crude estimate lies below the NIXT estimate of cool plasma densities. Giovanelli (1974) suggested that the interspicular medium has a typical density of  $\sim 3 \times 10^{10} \text{ cm}^{-3}$  and is confined primarily to heights of  $\sim 3500$  km. As seen in figure 14, this interspicular medium density falls within the distribution of densities from the NIXT estimate at 3500 km, while above 7000 km, the spicular mass estimate overlaps with the NIXT estimate. Thus, within the large errors involved, it seems that there is room for agreement between the NIXT neutral hydrogen density estimate and the off-limb  $H\alpha$  observations.

The NIXT observations indicate that material at chromospheric temperatures extends to heights above the footpoints of coronal loops, and is responsible for obscuring these footpoints when viewed by NIXT off the limb. This cool material has been observed in absorption before : *e.g.*, by reduced limb brightening in EUV transition region lines shortward of 912 Å (Withbroe 1970), and by absorption of the same lines above prominences at disk center (Schmahl & Orrall 1979). However, because the NIXT observes coronal lines, rather than transition region lines, it is able to observe that this absorption occurs not just above the transition region, but above the lower corona as well. Furthermore, the photospheric image in the 1991 February NIXT data allows us to establish the height above the visible limb of the observed X-ray intensities off the limb, which in turn allows us to infer the distribution of chromospheric absorption with height in the solar atmosphere. From the point of view of measuring the mass responsible for this absorption, observations above the limb, such as those presented in this paper, have the distinct advantage over on disk observations in that large amounts of this mass accumulate along the line of sight.

Although estimates of the average neutral hydrogen density may also be obtained from observations of  $H\alpha$  above the limb, the NIXT estimate has the advantage that any chromospheric mass will absorb X-rays passing through it, so that all the chromospheric mass residing in between coronal emission and the observer will be 'seen' in absorption, regardless of whether it exists in individual structures or a diffuse medium, what its velocity is along the line of sight, etc. Thus, any significant amount of mass missed by other chromospheric observations would be detected by these NIXT observations. The NIXT average neutral hydrogen density estimate has about an order of magnitude uncertainty, which arises primarily out of uncertainty about the location and amount of NIXT X-ray emission which is being absorbed. If a large sample of precisely aligned visible and X-ray images could be obtained by satellite, these uncertainties could be greatly reduced, both by performing time averages of the data and by performing on disk studies to determine the statistical distribution of coronal loop parameters. Such an undertaking could yield a more precise measurement of the average neutral hydrogen density *vs* height. Even with the limited data sample available, the NIXT observations constrain the average neutral hydrogen density *vs* height in the solar atmosphere in a way not previously possible. We hope that this will be a motivation for similar studies in the future.

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